General Considerations. Surface measurement devices generally consist of two major types: (1) those that use monuments and markers or targets to measure movements of the dam from a remote point, and (2) those that are mounted on the exterior or interior surfaces of the dam from which differential movements of portions of the structure are determined, including measurements at joints or cracks. The devices are used to measure total or relative horizontal, vertical, or rotational movements or differential movements in any desired plane.

Plumbline Descriptions and Reading Methods.

Usage. Plumblines represent a convenient and relatively simple method of measuring the manner in which a concrete dam moves due to applied reservoir water pressures and temperature changes. In early Bureau dams where elevator shafts were provided, Plumblines were located in the elevator shafts. That practice generally proved to be unsatisfactory because of mechanical- or airflow-induced vibrations in the plumb line wire.

For the more recently built Bureau dams, the Plumblines have been suspended in vertically formed wells that extend from the top of the dam to near the foundation, generally at three or more locations in the dam. Wherever feasible, reading stations are located at intermediate elevations, as well as at the lowest possible elevation, to measure the deflected position of the dam section over the full height of the structure. Plumblines may also extend into the foundation in drill holes.

Description of Devices. Plumbline installations of two general types have been used, the weighted plumbline and the float-suspended or inverted plumbline. The installations consist of a formed shaft, suspension assembly, wire, plumb bob, dashpot, and reading stations and, for float-suspended types, a tank and float assembly.

Shaft. The shafts or wells are usually 1 foot (0.3 m) in diameter, and are constructed to within 0.5 inch (13 mm) of plumb as the dam increases in elevation. In some dams, pipe or casing has been used to form the shaft and has been left in place, while in other dams; the shafts have been formed using slip-forms. Pipe casing left in place has, in some cases, resulted in problems with corrosion and rust flaking.

Suspension Assembly. For the conventional plumbline, the wire is suspended at the upper end of the pipe shaft using a collet and nut inserted in the center of a steel suspension assembly placed over the pipe opening. Alternatively, other devices, such as a pulley and locking spool, could be used to suspend the plumb bob. Watertight gaskets and sealing materials are used to prevent entry of water into the shaft and to reduce corrosion of the plumbline apparatus.

Wire, Plumb Bob, and Dashpot. The plumbline wire is usually of stainless steel or other high-strength, corrosion-resistant steel wire that is 1/64 inch in diameter. A 15- to 25-pound plumb bob is normally used, and is also constructed of a corrosion-resistant metal. To damp the pendulum action of the wire and plumb bob and to minimize local vibrations of the wire, an oil-filled container is provided at the lowest reading station for immersion of the plumb bob. A no corrosive oil such as Plurasafe P1200C should be used. This dashpot must be at least 4 inches larger in radius than the plumb bob to allow for free deflection. When moisture or condensation is excessive, a deflecting metal cover may be clamped around the wire a short distance above the dashpot to prevent water contamination of the oil.

Reading Stations. The reading stations on a plumbline shaft are located in the galleries at different elevations in the dam. A doorframe is set in the concrete of the gallery wall at each reading station, and doors seating against rubber seals are provided as closures. The doors of the reading station should remain closed and locked to prevent disturbance to the plumbline.

If possible, reading stations are oriented so that measurements may be made in the directions of anticipated movements, thereby avoiding the need for trigonometric resolution. In some older dams, orientation of the reading stations requires that measurements be made at 45^{E} to the direction of dam movement, thus necessitating computations to determine radial and tangential components of movements.

Measurements of deformation are made with a micrometer slide device having either a peep sight or microscope for viewing. The measured movements indicate deformation of the structure with respect to the plumbline suspension point. The readings are also readily adaptable to automated reading systems.

Tank and Float Assembly for Inverted Plumbline. A few recently installed plumbline installations are float suspended, using antifreeze in a tank near the top of the dam, with a float holding the wire. In this type of installation, the lower end of the plumbline is fixed near the bottom of the dam and movements are observed near the top and at intermediate stations.

Advantages and Limitations. Advantages of plumbline devices include high accuracy in movement measurements and, when observed over several years, will furnish information regarding the general elastic behavior of the entire structure and foundation. These data also provide a means for determining the elastic shape of the deflected structure and, with precise alignment data, provide for the estimation of the amount of translation of the structure.

Limitations of conventional plumbline usage include the requirement of trained observers for securing the readings, possible corrosion of metal components in the system, and the fact that no readings can be obtained until completion of the structure to its full height. With inverted Plumblines, measurements can be made during construction.

Maintenance and Repair Procedures.

Shaft and Reading Station. The process of forming the reading station recess is a routine construction procedure and is included with other form work in the construction contract. The plumbline shafts were made by installing lengths of metal pipe vertically from below the lowest station up to the suspension point. Spiral welded pipe or drill hole casing pipe were found satisfactory for this purpose although problems with rust flaking have been experienced. Special care in alignment and bracing during concrete placement was necessary to ensure plumb ness of the pipe sections and to ensure a clear projected net opening approaching the full size of the pipe.

Suspending the Plumb Bob. It was important that the permanent plumbline be located at or near the center of the net opening of the shaft. A method that was successfully used goes as follows: center point may be determined by suspending a surveying plumb bob on a string or cord of a length sufficient to reach from the top of the shaft to the lowest reading station. A sheet of cardboard is then secured in place directly beneath lower end of shaft, and a pattern of the clear projected net opening of the pipe is established by marking the positions of the plumb bob as the suspension cord is moved around the periphery of the shaft at the top of the shaft. The plumb bob

should be allowed to come to rest at each of the 8 to 10 points required to define the clear opening pattern. With the cardboard still in place, the center of the pattern is established within 3 inch and is projected to the top of the shaft using the temporary plumbline. The permanent plumbline is then set as close to the center as practicable.

Installing the permanent plumbline is not a difficult operation, but must be accomplished with care to avoid kinks or twists in the wire. A method that was used is as follows: the wire, which has previously been wound on a spool in a reeling rack, is threaded through the collet in the plug, through suspension assembly, and then attached to the plumb bob. On some plumb bobs, the cap may be removed and the connection made by threading the wire through the hole in the center of the cap which contains a cone-shaped recess. The wire is twisted around a short nail, and then hot solder is poured in to cover the nail and fill the cup. After solder has cooled, the cap is lowered through the shaft to the lower reading station. When the cap is at the level of the damping pot, cap is screwed onto plumb bob, lowered into damping pot, and sufficient oil added to cover plumb bob. The freely suspended bob is then adjusted to an elevation just below the oil surface and the wire permanently fixed at the suspension point.

For the tank and float-suspended Plumblines, the center of the shaft is found as before, and the wire is fixed at the bottom and fastened to the center of the float device at the top. The tank at the top can be moved to allow for centering the float device.

Reading Stations. The position of the four bars (two microscope mounts and two reference bars) attached to the bar support plates in the reading stations is dependent on the following:

Maximum expected movement of plumbline; Mechanical working distance of the microscope (distance from front of objective lens mount to the object plane); Length of the telescope draw tube travel (external range of rack and pinion movement of objective lens mount); and the offset dimensions of micrometer support clamp.

The positions are established by consideration of the extreme positions of the plumbline during maximum deflection due to reservoir load and the estimated annual temperature deflection cycle. Both the annual temperature deflection cycle and the maximum load deflection cycle are superimposed upon the estimated permanent thermal deflection to obtain the maximum possible range normal to the axis of the dam. Transverse movements are generally small and difficult to predict, so an allowance of about 10 percent of the total estimated movement normal to the axis of the dam is provided in the lateral direction. The reference bars and slides are then mounted to allow such movement to be accurately measured.

Inverted plumbline stations have a clear plastic rectangular plate attached to the top of the float tank. This plate is marked so that the movements of the plumbline can be measured in two directions, upstream/downstream and left/right. The plumbline pointer assembly attached to the plumbline wire and the surface tank float moves, the deflections can be scaled from this plastic plate.

Maintenance. A light film of oil should be maintained on the reference and support bars to provide protection against corrosion. It is necessary to wipe away this oil immediately prior to taking readings. After readings are obtained, replace the light film of oil. The oil in the damping pot should be maintained at the proper level.

When not in use, micrometer slides, micrometers, and microscopes should be kept in their carrying cases and stored in a safe, dry place. This apparatus must be handled with care at all times. One or two drops of light lubricating oil may be applied to the exposed screw threads and sliding surfaces of the micrometer at intervals of several months. It is suggested that a soft brush and tissue paper be used for removing dust, as necessary. The inverted system should be inspected for alignment and for proper fluid level in tank.

For regular plumblines (suspended type): The oil in the basin or pan within the basin should cover the plumb bob to dampen movements. Any 20 weight oil would work, but Plurasafe P1200C oil (BASF Corporation, Chemicals Division, was chosen because it is soluble in water and when water drips into the oil from above, the water stays on top instead of sinking to the bottom and displacing the oil (displaced oil would eventually overflow and all that would remain would be the water). This oil is water-soluble and should be premixed in 10 or 12 to 1 water: oil ratio. To prevent evaporation, a light coating or layer of machine, general purpose, mineral, or automotive oil should then be put on the surface of the Plurasafe oil (about a pint). Maintenance consists of keeping the oil clean and/or changing it annually, and keeping the microscope or peep sight viewer clean. A MSDS (Material Safety Data Sheet) is available in the D-8460 files.

Data Collection. -- The micrometer, micrometer slide, and microscope are precision instruments and should be used in a manner consistent with good laboratory practice. The same person should preferably make all microscope readings; however if that is not practicable, a new observer must be thoroughly trained in instrument usage.

To take a reading, the micrometer, slide assembly, and microscope are fixed into a position such that the reading will fall within the range of the microscope. All clamps are then fixed, and the microscope always started from the left-hand side. The screws are turned so that the objective lens approaches the plumbline wire from the left side. Continue turning the screws until the wire is precisely sighted, and then a reading is taken. If the screws are turned to a point where the lens is focused to the right side of the line, the microscope must be returned some distance to the left and the line approached again. The screws should never be reversed just prior to making a reading.